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IMPROVEMENT OF HEAD-UP DISPLAY STANDARDS

Volume II: Evaluation of Head-Up Displays to Enhance Unusual Attitude Recovery

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Summary

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Table of Contents

List of Tables

List of Figures

INTRODUCTION

The current HUD program has as its objective the development of general specifications for head-up displays (HUDs). It is divided into five tasks. Tasks A and B are flight test evaluations of various HUD dynamic responses and accuracies with the overall objective of developing criteria for approving HUD characteristics in these two areas; Task C is a symbology evaluation in a ground-based simulation (and is the subject of this report); Task D is the preparation of a strawman HUD specification; and Task E is the assessment of HUD safety issues -- notably HUD factors influencing spatial disorientation.

Task C is a simulation evaluation of several symbologies with the aim of selecting appropriate ones which will facilitate pilot recognition of and recovery from unusual attitudes (UAs).

BACKGROUND

One of the potential problems identified during recent HUD instrument conferences is an inability of the pilot to recognize when he is in an unusual attitude (UA) and then to recover using the HUD.(1-3) The problem arises from a variety of causes. These causes (in no particular order) are

- Lack of color codes to identify erect from inverted flight;
- Lack of texture cues in the HUD similar to those found in attitude indicators to identify erect from inverted flight;
- Excessive amount of data present in the HUD in the form of digital data boxes, etc., which are useful during selected phases of flight, but do not assist during UA recovery;
- Difficulty in assessing rate information with digital airspeed and altitude presentations;
- Small field-of-view (FOV) combined with full scale angles (which are helpful during normal flight) which make assessment of the overall situation difficult;
- Accommodation traps in the HUD symbology or in the combiner structure which cause the pilots eyes to accommodate to a distance much less than optical infinity;
- Use of the velocity vector (GAMMA) as a control parameter rather than as a performance parameter.

Any solution to enable the HUD to be useful during UA recognition or recovery must address these topics. It must be pointed out that many of these issues apply equally to electronic attitude displays (EADIs, etc.).

Lack of Erect versus Inverted Cues

The conventional attitude (director) indicator (ADI) uses black (or brown) and blue (or light grey) hemispheres to distinguish erect from inverted flight. The ADI also provides patterns on one or both hemispheres to simulate ground texture or clouds.

Most also use a stylized airplane symbol to emphasize aircraft attitude.

The HUD, on the other hand, is limited in that it must use monochromatic lines and avoid texture cues which might block external visual cues. It is unlikely that color HUDs will be able to provide sufficient color contrast in the near future. It is also impractical to expect the blue or brown colors denoting sky or ground to be available for HUDs regardless of technology, because a blue symbol would not be clearly visible against the sky and a brown symbol would not have sufficient contrast against some terrain features.

In this respect, HUDs are similar to first generation artificial horizons. It is interesting to remember that, originally, unusual attitude recovery called for the pilot to roll to the nearest horizon. This could leave the pilot erect or inverted, however, the aircraft would be stabilized.

In place of color coding the HUD, other approaches must be taken. One is to use solid versus dashed lines above and below the horizon. Plus and minus numbers are used as well. It is unlikely that these can be entirely successful, by themselves, during the dynamic situation of an unusual attitude.

Other approaches include asymmetric pitch lines (inverted flight places these lines on the other side of the HUD). This would make it easier to recognize erect from inverted flight, but would do little to assist in identifying extreme nose-up from nose-down attitudes. A similar, but less extreme format was proposed by Taylor of the RAE.(4)

Different pitch scalings above and below the horizon have been suggested to aid in identifying nose-high and nose-low situations.

The F-18 HUD uses slanted pitch lines at large pitch angles to indicate the direction to the horizon. Another cue could be a bank index (a sky or ground pointer). Still another would be to add the words "DIVE" and "CLIMB" as is done on many ADIs.

Clutter

During UAs, HUD clutter can prevent the pilot from interpreting the cues needed for prompt recognition and recovery. Clutter has been defined in a draft FAA Advisory Circular as "A cluttered display is one which has an excessive amount of information in the number and/or variety of symbols, colors, and spatial position relationships. A large fraction of this information may be pertinent to the task at hand, but if an evaluation shows that the secondary information detracts from the interpretation necessary for the primary task, or increases the display interpretation error rate, irrelevant or lower priority information should be removed."(5) The two-and-one-half degree pitch line spacing on the early F-16 HUD has been criticized in this regard. Excessive data has also been criticized. In extreme situations. almost complete declutter (even to the point of deleting required parameters, such as heading) may be required.

Lack of Rate Information

The use of digital displays has been criticized by some pilots in making the determination of rate information difficult. This may be more of a problem with determining airspeed rate than altitude rate, since the velocity vector will allow the pilot to control his altitude rate during normal flying. It is not clear how this will or will not affect UA recognition and recovery. Possibly the flight path acceleration cue proposed by the French could be of some use here.(6)

Pitch Scaling

It can be difficult to assess the situation using a full scale but limited FOV display. The conventional ADI is cruder, but its compressed scale makes recovery easier. Studies have been performed to examine the benefits of compressed pitch scaling during large amplitude maneuvers.(7) These results indicate that pitch scale compression can be a help during air combat maneuvers (ACM) or acrobatics.

Early HUD studies in the United Kingdom also showed that a slight pitch scale compression produced tighter approach tracking than one-to-one scaling.(8-9) Compressed pitch scales may help during UA recognition or recovery as well. They have been recommended by Freiburg as well.(10)

Accommodation Issues

The issue of accommodation traps has been raised by Roscoe and his students.(11-12). Briefly, the argument is that the HUD symbology, in spite of being collimated, will not allow the pilot's eyes to accommodate to optical infinity but will focus much closer to a distance approximating the dark focus point (perhaps one meter in front of the pilot's eye). This, they assert, will cause large shifts in accommodation when the pilot fixates on objects in the real world. This rapid shift in accommodation between HUD images and real world images can be a major cause of vertigo.

We do not accept this argument completely. Based on interviews with operational pilots flying HUDs, Newman(13) found virtually no mention of eye discomfort, focusing problems, or anything resembling accommodation difficulties. Subjectively, we find that flight in rain in a HUD-equipped airplane allows much clearer view through the HUD combiner than around it. When the HUD symbology is turned off, view through the combiner or around it is equally clear (about the same as the previous view around the combiner. The conclusion, a subjective observation, is that the symbology makes the real world clearer and more in focus. We will suggest that the raindrops and streaks on the windshield act as accommodation traps to a eye-windshield distance and that the HUD symbology act as traps to a further distance.

In any event, the resulting accommodation distance would be at least as far as the conventional instruments and there have been no suggestions to date that changing from head-down instruments to the real world causes disorientation.

A more subtle form of disorientation can result from the narrowing of the visual field as the eye accommodates to the dark focus point. This may produce errors in judging distance and angles to an outside visual target(14). This disorientation has no bearing on the issue of solid instrument conditions (IMC).

Use of GAMMA versus THETA

One potential problem is the practice of pilots using the velocity vector as a control parameter. During normal flight, this presents no problems, but during UAs, particularly at large angles-of-attack (ALPHAs), this can create situations where the pilot needs to push, but is pulling because of the extreme negative GAMMA.

During discussions with operational fighter pilots during this and previous studies (13,15), it appears that they have only a superficial unders'anding of the implications of using GAMMA as a control parameter rather than THETA. Some HUDs do not even display THETA.

The A-7C/D/E HUD is often criticized for having the ALPHA display "backwards." This was designed to emphasize the unique relationship between THETA, GAMMA, and ALPHA. The Thomson HUDs, designed for transport airplanes made particular use of this relationship (16).

OBJECTIVES OF TASK C

The object of this study was to study the effects of HUD symbology changes on recognition of and recovery from unusual attitudes (UAs). The experiment used operational pilots as subjects, introduced them to UAs artificially, and required them to recover using the HUD for flight information. No head-down information was available to the subject pilots.

The subject pilots were also asked to perform some routine maneuvers using the HUD to evaluate the effect of the various symbologies on their normal operations. These maneuvers were originally to include tasks not involving dynamic flight (such as visual landing approaches) and tasks involving dynamic flight (such as acrobatics). Equipment difficulties precluded the visual approach task.

The following comparisons were planned: (Those enclosed in brackets [ ] were not evaluated; those enclosed in braces < > were added during the course of the simulation.)

- Effect of pitch ladder cues
  - o Symmetric vs. asymmetric
  - o Different spacing above and below horizon
  - o Combinations of above
  - o Slanted pitch ladder
  - [o Conventional above and slanted below horizon]
  - [o Elimination of controlled precession]

- Data presentation
  - o Digital vs. analog
  - o Automatic switching
  - [o Effect of extraneous data]
  - o Effect of no scales
  - o Automatic declutter
  - [o Flight path acceleration]
  - o "Minute hand" on data scales

- Effect of pitch scale compression
  - o One-to-one scaling
  - o Two-to-one scaling
  - o Six-to-one scaling
  - o Automatic switching

- Other cues
  - o Bank pointer
  - <o Location of bank pointer>
  - <o Arrow on velocity vector>
  - o Velocity vector only vs pitch only
  - <o Automatic deletion of velocity vector>

During this experiment, the emphasis was on pilot recognition of unusual attitude and recovery therefrom. For this reason, only air mass data was used.

EXPERIMENTAL DESIGN

Symbologies Evaluated

All symbologies were compared to a baseline HUD symbology based on the F-18 with several slight variations. This baseline symbology was also used as the baseline during NT-33A evaluations under tasks A and B. It is described in some detail in Reference (17).

The following are the set of symbologies to be compared. Again, some were not evaluated during the course of the experiment. These are shown with brackets [ ]. Selected symbologies are shown in Figure 1 (baseline), Figure 2 (analog scales), Figure 3 (improved minute hand), and Figure 4 (roll arrow on velocity vector -- Augie Arrow).

1. Baseline symbology;
2. 2 deg pitch ladder;
3. 5 deg pitch ladder above horizon and 2 deg below horizon (vertical asymmetry);
4. Pitch ladder on right side only (horizontal asymmetry);
5. Both vertical and horizontal asymmetry (combine symbologies 3 and 4);
6. Six-to-one pitch scale compression;
7. Two-to-one pitch scale compression;
8. Six-to-one pitch scale compression, automatically selected when pitch exceeds thirty degrees or bank exceeds sixty-five degrees;
9. Baseline symbology plus bank index at bottom (bank index limited to plus or minus thirty degrees);
10. F-18 style slanted pitch ladder;
11. Replace digital scales with analog scales (for airspeed and altitude only);

[12. Baseline symbology plus flight path acceleration cue (Reference 15);]

[13. Cluttered display;]

14. Analog scales which change to digital automatically when pitch exceeds thirty degrees or bank exceeds sixty-five degrees;
15. Analog scales and one-to-one pitch scale compression which change to digital scales and six-to-one pitch scale compression automatically when pitch exceeds thirty degrees or bank exceeds sixty-five degrees;
16. Delete scales automatically when pitch exceeds thirty degrees or bank exceeds sixty degrees;

17. Delete scales and change to six-to-one pitch scale compression automatically when pitch exceeds thirty degrees or bank exceeds sixty degrees;
18. Use "minute hand" to supplement airspeed and altitude scales;
19. Change from one-to-one pitch scale compression to two-to-one automatically when pitch exceeds thirty degrees or bank exceeds sixty degrees;
20. Baseline symbology plus bank scale at top of field-of-view (bank index free to move through 360 degrees);
21. Baseline symbology plus bank scale at top of field-of-view (bank index free to move through 360 degrees, index increases in size and is double written when roll exceeds plus or minus 58 degrees);
22. Improved minute hand: same as symbology 18 except readability of symbols improved;
23. Baseline symbology with winged W pitch symbol removed;
24. Roll arrow on velocity vector pointing to zenith (Augie Arrow);
25. Baseline symbology plus bank scale at top of field-of-view and roll arrow on velocity vector (bank index free to move through 360 degrees) (combine symbologies 20 and 24);
26. Baseline symbology plus bank scale at bottom of field-of-view and roll arrow on velocity vector (bank index free to move through 360 degrees);
27. Baseline symbology with velocity vector symbol removed;
28. Delete velocity vector automatically when pitch exceeds thirty degrees or bank exceeds sixty degrees;
29. Delete velocity vector automatically when angle of attack exceeds ten degrees;

[30. F-18 style pitch ladder below and conventional (baseline) pitch ladder above horizon;]

[31. Roll arrow on velocity vector pointing to zenith (Augie Arrow) displayed automatically when pitch exceeds thirty degrees or bank exceeds sixty degrees.]

Subject Pilots

The six subject pilots for this simulation study had an operational background. Their background was one-third air-to-air, one third air-to-ground, and one third transport. The subjects were half HUD-experienced and half HUD-inexperienced. Table I summarizes the experience and background of each subject pilot.

Each subject pilot was briefed prior to flying the simulator. This briefing included:

- Description of the experiment;
- Review of simulator and experiment "ground rules;"
- Completion of a questionnaire
  - Pilot experience
  - HUD experience

Each pilot was debriefed following the experiment. This included completing a post-experiment questionnaire asking for subjective evaluations of the merits of the various symbologies.

Several subjects (U, W, Y, Z) participated on several occasions. On second and subsequent trials, the description of the experiment and the questionnaires were omitted. The subjects were given a brief review of the evaluation ground rules.

Equipment Description

The simulations were flown in the TASTEF simulator at Patuxent River NAS. The TASTEF simulator was constructed from an F-4 front cockpit with the conventional instrumentation replaced with multi-purpose electronic displays. None of the head-down displays were active during these simulations.

Airplane responses, visual displays, and control loading are generated by several minicomputers operating in parallel. The basic airframe response was that of an F-14A in the clean configuration. No cockpit motion was available.

The visual display consists of an Evans and Sutherland monitor with both stylized real world scenes and detailed HUD symbologies shown on the same monitor. For the unusual attitude recoveries and instrument evaluations, the real world scene was not visible.

The TASTEF simulator is described in Reference (18).

Flight Profiles

The flight profiles consisted of sufficient time for the subject pilots be become familiar with the particular symbology set. When sufficient time was reached (as decided by the subject pilot himself), the pilot was placed in instrument conditions and the simulator reset to four separate unusual attitudes. The pilot was told when to expect the UA and he advised the simulator operator when the recovery was completed. Control position, airspeed, heading, pitch attitude, roll attitude were recorded during these recoveries.

Following recovery from the fourth UA, the visual scene was restored and the pilot directed to fly a series of acrobatic maneuvers: loops, barrel rolls, and cloverleafs. He was then given the opportunity to fly any maneuver he wished in an attempt to evaluate the suitability of the HUD.

Generally, the subject pilots reported that they were ready to fly data points within four or five minutes. The first or second data run usually required additional familiarization time.

The unusual attitude initial conditions are shown in Table II.

Experimental Protocol

The sequence of each subject pilot's evaluation consisted of a briefing which included the completion of the initial questionnaires. Following this, he was given sufficient practice with the baseline symbology to satisfy himself of familiarity with the simulator and HUD. One hour was allowed for this practice.

Following this, each pilot was given experimental displays in turn with practice, four unusual attitudes, and acrobatic evaluations as described above. Generally two subjects were present and alternated simulator sorties. The pilot not flying used the intervening time to complete a post-sortie questionnaire. No instructions were given to thee pilots concerning UA recovery technique other than to use their own experience. They were told that the recoveries would be recorded.

The order of presenting unusual attitudes and the order of presenting symbologies was randomized to minimize learning effects.

Following the completion of the sessions, each subject completed a post-experiment questionnaire.

Generally, symbologies 1-18 were completed with all six subject pilots. Following a review of the data, symbologies 1, 7, 8, and 19-29 were flown with subject pilots U, W, Y, and Z.

Table I

Subject Pilot Background

Pilot	Total Time	Flying Background	HUDs Flown
U	3000	Air-to-ground	F-16,DEFT(a)
V	2000	Air to-ground	None(b)
W	2700	Air-to-air	F-15, DEFT
X	1500	Air-to--air	None
Y	2700	Transport	DEFT
Z	5100	Transport	Several,DEFT

(a) DEFT is the programmable HUD in the AFWAL NT-33A airplane used in Tasks A and B of this study. Several subject pilots participated in both studies.
(b) This subject had flown 30 hours in F-16 aircraft, but was not F-16 qualified at the time of the simulations. He was not currently holding a flying position.

Table II

Unusual Attitude Initial Conditions

Pitch	Bank	Airspeed
30 deg	165 deg	175 knots
85	30	145
0	90	175
-10	15	450
-10	165	450
45	135	175
-30	45	450
10 deg	165 deg	450 knots

Note: All initial altitudes were 15000 feet.

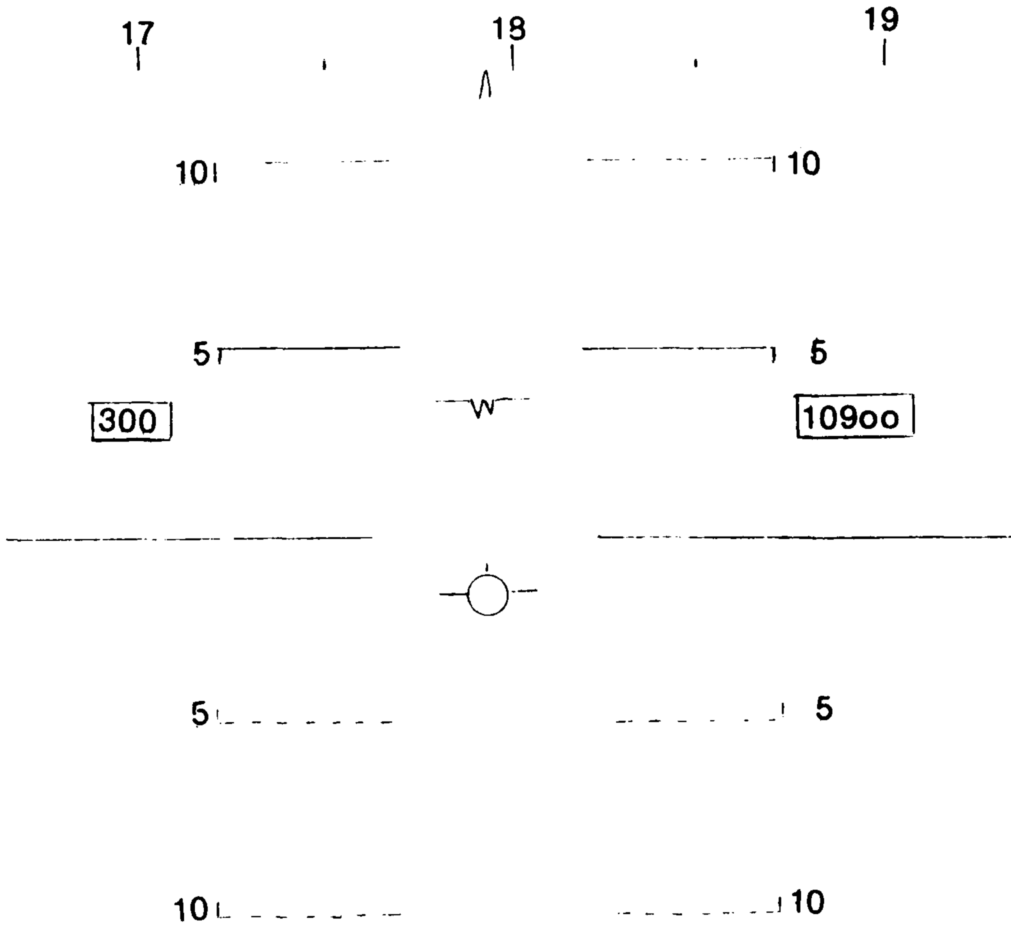

Figure 1

Baseline Symbology (1)

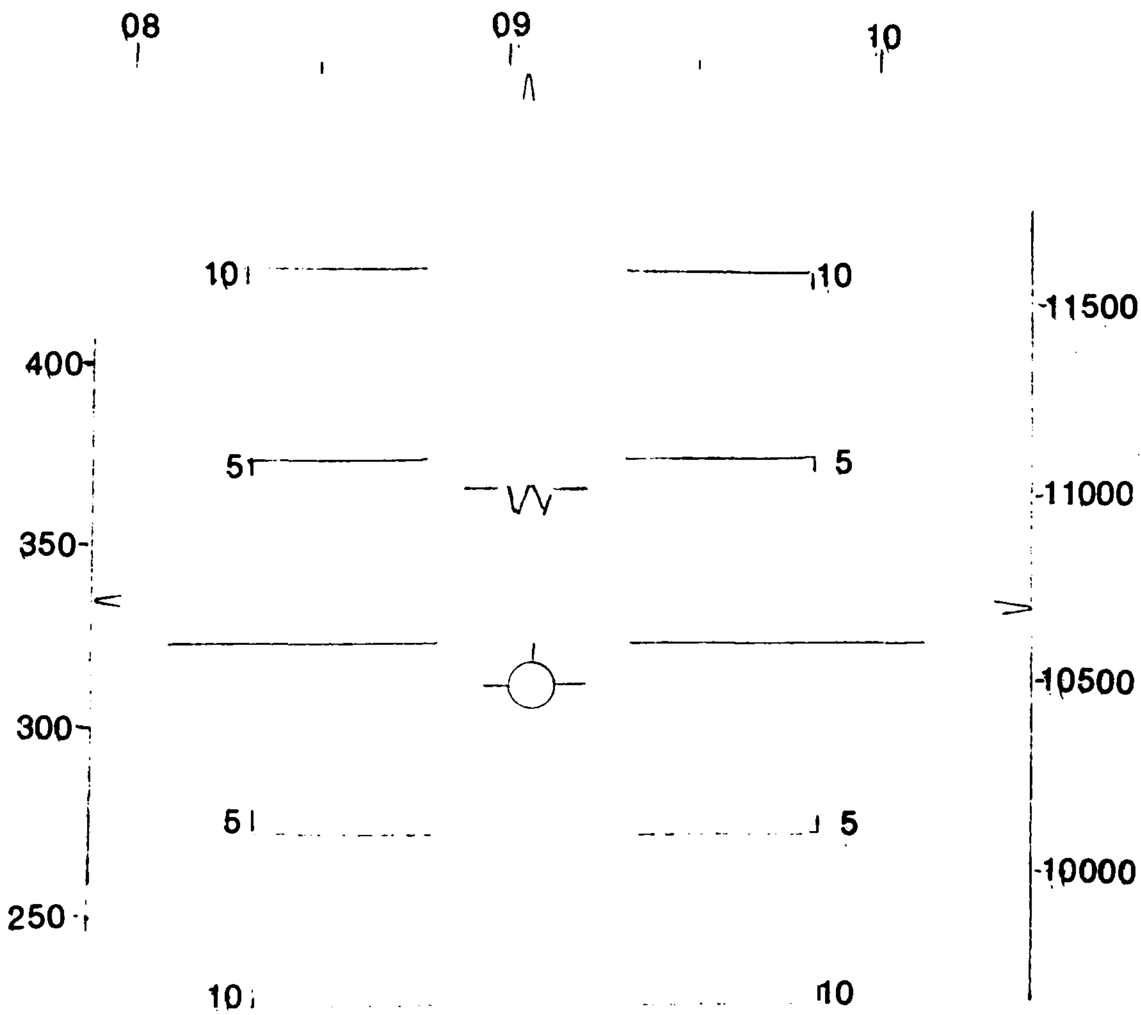

Figure 2

Analog Scales Symbology (11)

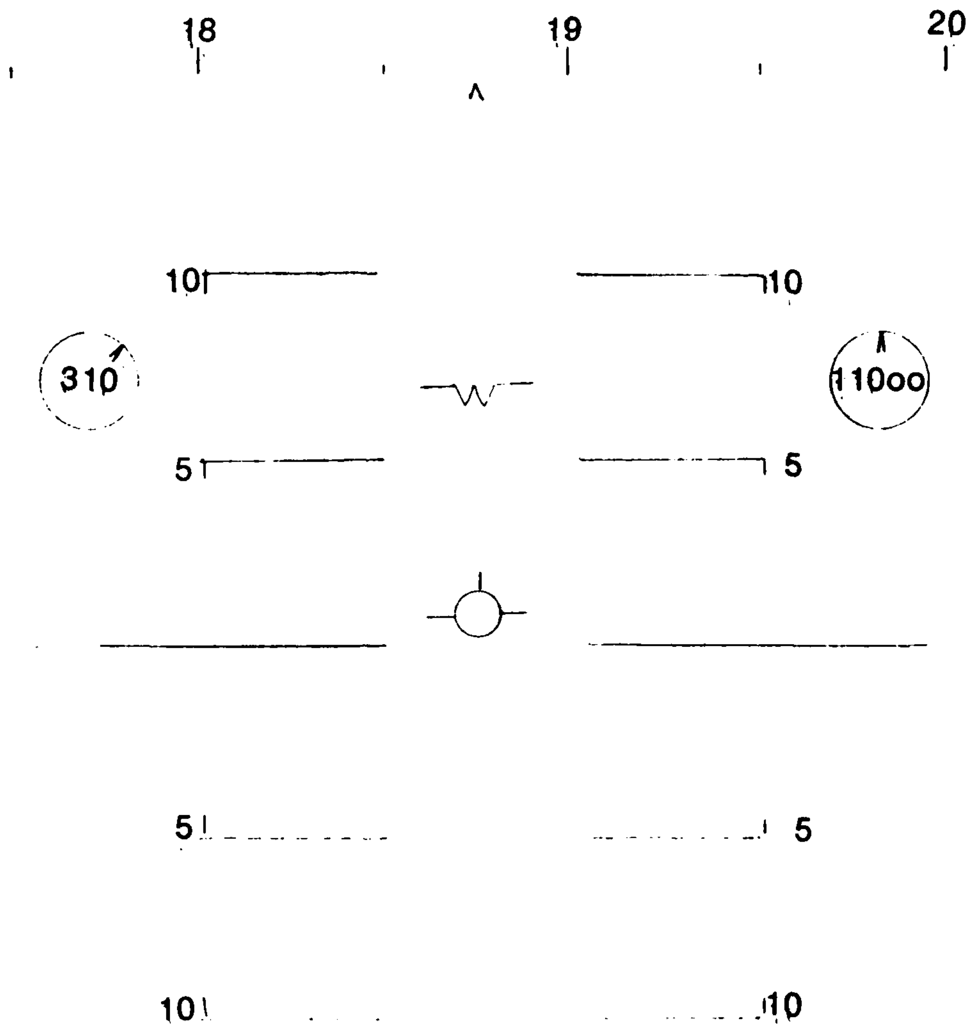

Figure 3

Improved Minute Hand Symbology (22)

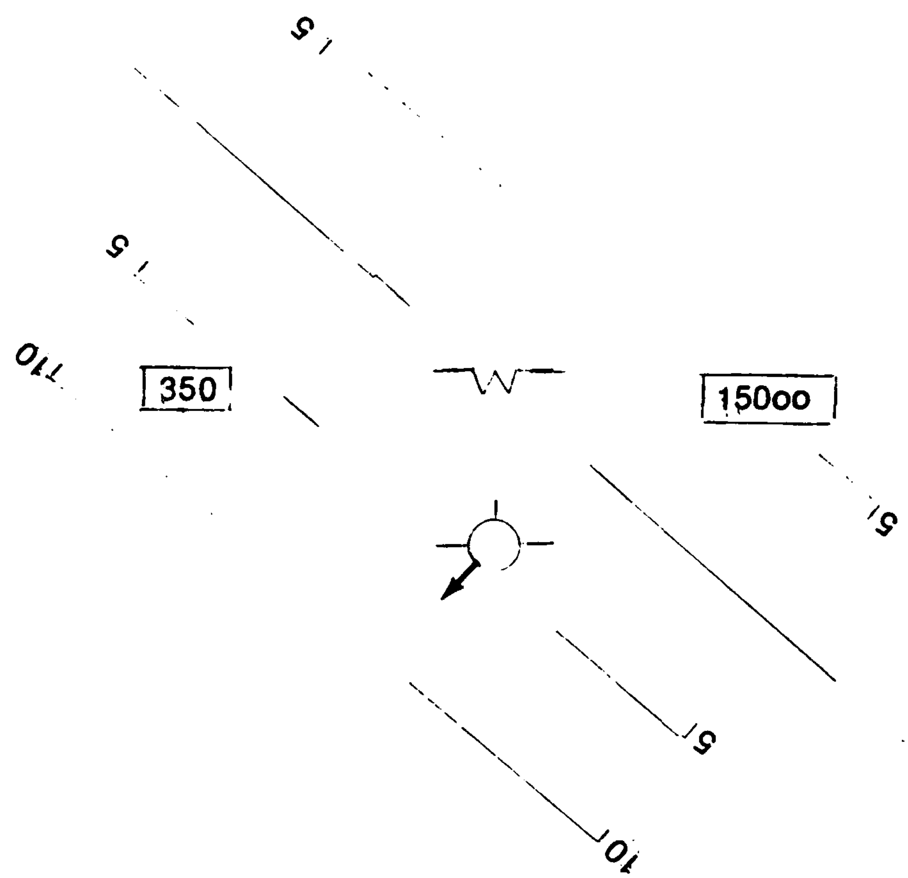

Figure 4

Roll Arrow on Velocity Vector Symbology (24)
(Augie Arrow)

RESULTS

Subjective Data

The subjective data was obtained from questionnaires which the subject pilots completed following each data sortie with an experimental (or the baseline) symbology. Each subject also completed a final debriefing questionnaire following the experiment.

Post flight subjective ratings

The post-flight questionnaire asked the subject pilot to rate the display in terms of ease of flying, ease of maintaining spatial orientation, and his overall rating of the display. The pilot was asked specifically to separate phases of flight for his ratings and was specifically asked for the ratings both overall and during unusual attitude recoveries. Table III summarizes the results.

In this summary, the data for symbology 29 (one trial) was combined with that for symbology 28. These symbologies involve automatic deletion of the velocity vector symbol and differ only in the specific parameters chosen to trigger this deletion.

Pitch scale compression

This will be difficult to extract meaningful conclusions. It is necessary to examine related display concepts. For example, if we examine the various pitch scale compression, we have one-to-one (baseline, symbology 1), two-to-one (symbology 7), six to-one (symbology 6), automatic two-to-one(symbology 19), and automatic six-to-one (symbology 8). The ratings for unusual attitude recognition and recovery for these five symbology formats are shown in Table IV. These ratings show a clear subjective preference for a two-to-one scaling with a slight preference for automatic switching over full-time two-to-one. While six to-one scale compression is down-rated, automatic six-to-one is rated below full-time six-to-one. Comments were made that this was too abrupt a change in compression.

In terms of the subject pilots estimate of the suitability of these various pitch scale compressions in their operations, the ratings were the same except that six-to-one compression was down rated greatly and automatic six-to-one down-rated slightly (but still behind full-time six-to-one.

Bank index option

Examining the various bank indication options, we have no bank index (baseline, symbology 1), a ground pointer limited to 30 degrees (symbology 9), a sky pointer free to move through 360 degrees (symbology 20), a sky pointer enhanced when bank exceeds 58 degrees (symbology 21), the sky arrow on the velocity vector (symbology 24), and a ground pointer free to move through 360 degrees combined with the sky arrow on the velocity vector (symbology 26). The ratings for unusual attitude recognition and recovery for these six symbology formats are shown in Table V. These ratings show a clear subjective preference for the sky pointer on the velocity vector, preferably with another bank index. There was also a preference for a ground rather than a sky pointer, but this may have been because of interference with the heading scale which is at the top. The combination of the ground pointer on the periphery and the sky pointing arrow on the velocity vector does have mixed cues.

In terms of the subject pilots estimate of the suitability of these various bank indices in their operations, the ratings were the same except that the worse ratings tended to be rated slightly lower overall than for UA recovery. The order is still unchanged from the overall rating in the Table, but with symbologies 9 and 20 a distant fifth and sixth.

Scales options

Examining the various airspeed and altitude scale options, we have digital scales (baseline, symbology 1), analog scales (symbology 11), digital scales surrounded by analog "minute hands" (symbology 18), an enhanced "minute hand" (symbology 22), scales that switch from analog to digital during unusual attitudes (symbology 14), and automatically deleting scales during UAs (symbology 16). The ratings for unusual attitude recognition and recovery for these six symbology formats are shown in Table VI. These ratings show a clear subjective preference for digital scales. One additional format was attempted, automatic scales change from analog to digital coupled with pitch compression. This format was so bad that it appeared pointless to continue. The two subjects who flew it said that it was unflyable.

In terms of the subject pilots estimate of the suitability of these options for use in operations, these estimates were identical for all displays as the overall rating in the table except for a slightly lower rating for symbology 18. The order is still unchanged.

Other format options

Examining other options generally in the pitch ladder format and in the use of velocity vector, we have the comparisons in Table VII. These ratings show a clear subjective preference for the baseline or F-18 style pitch ladders and for automatic deletion of the velocity vector when it is no longer appropriate (or dangerous) to use it. No clear preference for these three options was established. The various pitch ladder asymmetries were not well received by the subject pilots.

In terms of the subject pilots estimate of the suitability of these options for use in operations, these estimates were identical for all displays as the overall rating in the table except that display was very much down-rated to last. Symbology three was uprated slightly.

Comments made regarding formats

The evaluation pilots made comments concerning particular formats during the course of the simulation. These comments were contained in the post sortie questionnaires. The comments are listed in Appendix I.

General comments concerned inability to read the digits, the need for an enhanced horizon line, the need for a bank scale, and the problems induced by the apparent precession as the airplane passed through 90 degrees pitch (both pitch up and pitch down). Particular needs which were expressed by the subject pilots are shown in Table VIII.

Comments regarding upset modes

The evaluation pilots were generally not in favor of automatic upset modes. Three were not in favor, while three tempered their comments somewhat. The following comments were received:

Pilot U:	Initial comments said "Not convinced that the upset mode is a smart idea. Could lead to disorientation/misorientation. Subsequent ratings were neutral to slightly favorable
Pilot V:	During dynamic maneuvering very disconcerting and maybe in itself disorienting
Pilot W:	Could be useful. Not totally sure we need 'em. Also, exactly what is going to be "upset."
Pilot X:	No!
Pilot Y:	Must be careful in using these. Don't remove airspeed and altitude. Not too much of a scale change. i.e. from 1:1 to 2:1.
Pilot Z:	Some type of declutter would be good. Well worth researching.

Upset mode questions were also asked on the final debriefing questionnaire. The results are shown in Table IX. The ratings in this table are generally in agreement with the comments above.

The pilots were also asked to indicate triggers for these upset modes. Suggested trigger values for excessive bank and pitch are also indicated in Table X.

Post-experiment subjective ratings

The post experiment questionnaire asked each subject pilot questions concerning several issue raised during the evaluation: the use of non-conformal scaling; the value of the different changes to the display; and the use of automatic scaling or scales changes. The results of these post-experiment questions are summarized in Tables XI and XII.

Objective Data

The objective data was obtained from recording control motion, airspeed, altitude, and load factors during each unusual attitude recovery. Equipment difficulties made the load factor data invalid on most recordings. No load factor data was used.

The airspeed excursion data is also suspect since the instructions to the computer operator and subject pilots did not indicate when the recovery was completed. Many recordings had large airspeed excursions simply because the pilot allowed his speed to change greatly while the simulator was being reset. Table XIII summarizes the objective data.

While the number of trials for objective data should be identical to the number for subjective data, there were some instances where data was lost during recording. Generally, each "flight" represents four unusual attitude recoveries.

Initial control input

Perhaps the most meaningful objective data available is the pilot's initial control input. One measure of merit for a display is the length of time for the pilot to make the first correct control input. This was recorded. In addition, the percent of time that the pilot's first control input was in the correct sense was recorded. If the pilot's first control input was made at 0.8 seconds, but was incorrect and corrected at 1.0 seconds, this was recorded as a reaction time of 1.0 seconds with an initial error. Table XIV shows the various results ranked by reaction time. Those formats with one or two trials were omitted.

Table XV shows the data ranked by percent incorrect.

Altitude lost during recoveries

The objective data summarizing the recoveries ranked by altitude lost is shown in Tables XVI.

Pitch scale compression

The five variations in pitch scale compressions, one-to-one (baseline, symbology 1), two-to-one (symbology 7), six to-one (symbology 6), automatic two-to-one(symbology 19), and automatic six-to-one (symbology 8), are summarized in Table XVIII. The objective data in Table XVIII is ranked by reaction time.

Bank index option

Examining the various bank indication options, we have no bank index (baseline, symbology 1), a ground pointer limited to 30 degrees (symbology 9), a sky pointer free to move through 360 degrees (symbology 20), a sky pointer enhanced when bank exceeds 58 degrees (symbology 21), the sky arrow on the velocity vector (symbology 24), and a ground pointer free to move through 360 degrees combined with the sky arrow on the velocity vector (symbology 26). The ratings for unusual attitude recognition and recovery for these six symbology formats are shown in Table XIX. As before, the formats are ordered by reaction time.

Scale options

Examining the various airspeed and altitude scale options, we have digital scales (baseline, symbology 1), analog scales (symbology 11), digital scales surrounded by analog "minute hands" (symbology 18), an enhanced "minute hand" (symbology 22), scales that switch from analog to digital during unusual attitudes (symbology 14), and automatically deleting scales during UAs (symbology 16). The ratings for unusual attitude recognition and recovery for these six symbology formats are shown in Table XX.

Other format options

Examining other options generally in the pitch ladder format and in the use of velocity vector, we have the comparisons in Table XXI.

Table III

Post-Flight HUD Ratings (a)

Display	No of flts	How Easy to fly? (b)			How easy to maintain orientation? (b)			Overall Rating(b)			
		ACR	UAR	OVR	ACR	UAR	OVR	ACR	UAR	OVR	OPS
1 Baseline	7	3.1	2.6	3.0	2.6	2.9	2.7	3.0	3.0	3.0	3.0
2 2 Deg PL	1	4.0	3.0	4.0	3.0	3.0	3.0	5.0	4.0	5.0	5.0
3 +5/-2 PL	3	5.3	5.0	5.0	5.0	4.7	5.0	5.3	4.7	5.0	4.7
4 Rt side PL	3	4.7	4.0	4.3	4.0	4.3	4.3	5.0	3.7	4.0	4.0
5 Combine 3/4	2	5.5	4.0	4.5	4.0	4.0	3.5	5.5	4.0	4.0	4.0
6 6:1 scaling	4	3.5	3.5	3.0	3.5	3.3	3.3	3.8	3.5	4.0	4.5
7 2:1 scaling	6	2.8	2.3	2.8	2.5	2.5	2.8	3.0	2.5	2.5	2.8
8 Auto 2:1	6	4.2	4.0	4.5	3.2	3.8	3.5	3.8	4.2	4.5	5.0
9 Bank ind. B	3	3.7	2.3	3.0	3.3	2.7	2.7	4.3	3.3	3.3	3.7
10 F 18 PL	3	4.7	2.7	3.7	3.3	2.0	3.3	4.0	2.3	4.0	3.3
11 Analog	3	4.7	3.7	4.7	4.7	3.7	4.7	4.7	3.7	4.3	4.3
14 Auto A to D	3	4.7	4.3	4.7	5.0	3.7	4.0	5.3	4.0	4.7	4.0
15 Auto D/6:1	1	2.0	4.0	4.0	3.0	3.0	3.0	4.0	5.0	4.0	4.0
16 Auto delete	2	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
17 Auto del 6:1	2	7.0	7.0	7.0	7.0	6.0	7.0	7.0	6.5	7.0	7.0
18 Minute hand	5	3.4	3.4	3.4	3.8	3.6	4.0	4.0	3.8	4.0	4.2
19 Auto 2:1	3	3.5	2.2	2.2	3.0	2.2	2.2	3.5	2.2	2.2	2.2
20 Bank ind. T	4	3.5	4.0	3.8	3.3	3.3	3.5	3.3	4.0	3.5	3.8
21 Bank ind. T	4	4.0	4.0	3.8	3.3	3.5	3.3	3.7	3.7	3.4	3.4
22 Imprvd MH	4	4.0	4.0	3.8	3.3	3.5	3.3	3.7	3.7	3.4	3.4
23 FP only	4	3.7	3.3	3.0	3.7	2.8	2.3	4.0	3.3	3.3	3.3
24 Augie arrow	3	2.5	2.3	2.7	2.5	2.3	2.7	2.8	3.0	3.0	3.0
26 Bank ind B	3	2.7	2.0	2.0	2.7	2.0	2.0	2.7	2.0	2.0	2.0
27 Pitch only	2	4.5	3.0	4.0	2.5	3.0	3.5	6.0	3.0	4.5	6.0
28 Auto del FP	3	2.3	2.7	3.3	2.7	3.0	3.3	2.0	2.7	3.0	3.0

(a) Scale 1 = very easy; 4 = medium; 7 = very difficult.
(b) ACR = During acrobatics; UAR = Unusual attitude recoveries; OVR = Overall rating; OPS = In your operations.

Table IV

Average Pitch Scale Compression Ratings

For Unusual Attitude Recognition and Recovery

Display Symbology Pitch Scale Compression	No of flts	Ease of Flying	Ease to Maintain Orientation	Overall Rating
19 Auto 2:1	3	2.2 (1)(a)	2.2 (1)	2.2 (1)
7 Two-to-one	6	2.3 (2)	2.5 (2)	2.5 (2)
1 One-to one	7	2.6 (3)	2.9 (3)	3.0 (3)
6 Six-to-one	4	3.5 (4)	3.3 (4)	4.0 (4)
8 Auto 6:1	6	4.0 (5)	3.8 (5)	4.5 (5)

(a) Numbers in parentheses following average ratings are the rankings of these ratings.

Table V

Average Bank Index Ratings

For Unusual Attitude Recognition and Recovery

Bank Index	No of flts	Ease of Flying	Ease to Maintain Orientation	Overall Rating
26 Augie arrow plus grnd pntr (360)	3	2.0 (1)(a)	2.0 (1)	2.0 (1)
24 Augie arrow	3	2.3 (2)	2.3 (2)	3.0 (2)
1 No bank index	7	2.6 (4)	2.9 (4)	3.0 (2)
9 Grnd pntr (30)	3	2.3 (2)	2.7 (3)	3.3 (4)
21 Enhanced sky pntr	4	3.3 (5)	3.0 (5)	3.3 (4)
20 Sky pntr (360)	4	4.0 (6)	3.3 (6)	3.5 (6)

(a) Numbers in parentheses following average ratings are the rankings of these ratings.

Table VI

Average Scales Format Ratings

For Unusual Attitude Recognition and Recovery

Scales Format	No of flts	Ease of Flying	Ease to Maintain Orientation	Overall Rating
1 Digital	7	2.6 (1)(a)	2.9 (1)	3.0 (1)
11 Analog	3	3.7 (3)	3.7 (4)	3.7 (2)
22 Enhanced MH	4	4.0 (4)	3.5 (2)	3.7 (2)
18 Minute hand (MH)	5	3.4 (2)	3.6 (3)	3.8 (4)
14 Analog to digital	3	4.3 (5)	3.7 (4)	4.0 (5)
16 Auto delete	2	7.0 (6)	7.0 (6)	7.0 (6)

(a) Numbers in parentheses following average ratings are the rankings of these ratings.

Table VII

Average Longitudinal Format Ratings

For Unusual Attitude Recognition and Recovery

Scales Format	No of flts	Ease of Flying	Ease to Maintain Orientation	Overall Rating
10 F-18 pitch ladder	3	2.7 (2)(a)	2.0 (1)	2.3 (1)
28 Auto delete vel vec	3	2.7 (2)	3.0 (4)	2.7 (2)
1 Conv pitch ladder	7	2.6 (1)	2.9 (3)	3.0 (3)
27 No vel vector	2	3.0 (4)	3.0 (4)	3.0 (3)
23 No pitch symbol	4	3.3 (5)	2.8 (2)	3.3 (5)
5 Both asymmetries	2	4.5 (7)	3.5 (6)	4.0 (6)
4 Lat asymmetry	2	4.3 (6)	4.3 (7)	4.0 (6)
3 Vert asymmetry	3	5.0 (8)	5.0 (8)	5.0 (8)

(a) Numbers in parentheses following average ratings are the the rankings of these ratings.

Table VIII

Comments Regarding Improvements

Improvement desired	No. of comments
Easier to read digits	4 pilots
Enhanced horizon line	3 pilots
Bank scale needed	3 pilots
Waterline in compressed modes not meaningful	2 pilots
Eliminate precession	2 pilots
Wider pitch lines	1 pilot
Put heading scale in box	1 pilot
Don't enclose scales in box	1 pilot
Put wider wings on waterline	1 pilot
Make heading parallel to horizon	1 pilot

Table IX

Automatic Features Beneficial in "Upset Modes"

Feature Rated	Rating by Evaluation Pilot(a)						
	U	V	W	X	Y	Z	Ave
Auto declutter	4	1	4	6	7	2	4.0
Auto pitch compression	4	6	5	7	2	2	4.3
Auto declutter and pitch compression	4	7	5	6	6	2	5.0
Auto change from digital to analog	3	5	5	7	3	4	4.5
Auto change from D to A and Pitch Compression	3	7	5	7	3	4	4.3

(a) 1 = very helpful; 4 = neutral; 7 = Not Helpful

Table X

What Should Trigger "Upset Modes

Trigger	Vote by Evaluation Pilot(a)						
	U	V	W	X	Y	Z	Vote
Excessive bank	Y	N	Y	N	Y	Y	4-2
Excessive pitch	Y	Y	Y	N	Y	Y	5-1
Combination of bank or pitch	Y	N	Y	N	Y	Y	4-2
Engage with paddle switch on stick	N	N	N	N	Y	Y	2-4
Cancel with paddle switch on stick	Y	N	N	N	Y	Y	3-3
Bank trigger	70		90		40T/90F	60	
Pitch trigger	45		30		-5/+15	30	

Table XI

Features Beneficial in Future HUDs

Feature Rated	Rating by Subject Pilot(a)						
	U	V	W	X	Y	Z	Ave
Pitch ladder on one side	7	4	7	6	4	6	5.7
Different spacing above and below horizon	7	7	7	7	3	6	6.2
Bank index	1	7	2	7	4	1	3.7
Minute hand	3	7	7	7	2	2	4.7
F-18 style pitch ladder	1	4	1	4	2	1	2.2
2:1 pitch compression	3	6	4	4	2	3	3.2
6:1 pitch compression		6	4	6	5	6	5.4

(a) 1 = Very Helpful; 4 = Neutral; 7 = Not Helpful.

Table XII

Digital Versus Analog Scales

Feature Rated	Rating by Subject Pilot(a)						
	U	V	W	X	Y	Z	Ave
Altitude	3	1	1	1	2	5	2.2
Airspeed	3	1	1	1	1	3	1.7
Heading	1		1		4	3	2.2

(a) 1 = Digital; 4 = Neutral; 7 = Analog

Table XIII

Objective Data Summary

	Display	No of flts	Reaction Time	Percent Incorrect	Altitude Lost	Airspeed Range
1	Baseline	5	1.48 sec	12 %	1168 ft	74 knots
2	2 Deg PL	1	1.13	0	126	10
3	+5/-2 PL	3	1.64	36	379	25
4	Rt side PL	3	1.59	9	312	25
5	Combine 3/4	2	1.58	43	194	20
6	6:1 scaling	4	1.63	43	675	55
7	2:1 scaling	7	1.64	16	470	34
8	Auto 6:1	6	1.31	5	709	48
9	Bank ind. B	4	1.24	33	892	68
10	F-18 PL	3	1.39	0	549	52
11	Analog	3	1.55	8	317	19
14	Auto A to D	3	1.61	18	1600	37
15	Auto D/6:1	1	1.55	25	249	22
16	Auto delete	1	1.63	0	141	10
17	Auto del6:1	1	1.75	50	643	24
18	Minute hand	5	1.54	11	1260	60
19	Auto 2:1	3	1.41	29	342	26
20	Bank ind. T	4	1.39	25	947	71
21	Bank ind. T	4	1.37	8	410	53
22	Imprvd MH	1	1.46	50	121	9
23	FP only	4	1.48	0	516	40
24	Augie arrow	4	1.31	11	515	61
25	AA + BI (B)	0	(a)	(a)	(a)	(a)
27	Pitch only	3	1.21	29	116	22
28	Auto del FP	3	1.13 sec	0 %	111 ft	6 knots
	Overall	78	1.45 sec	17 %	615 ft	43 knots
	Std. Deviation		0.16 sec	14 %	388 ft	20 knots

(a) No objective data recorded for this format

Table XIV

Objective Data Ranked by Reaction Time

	Display	No of flts	Reaction Time	Percent Incorrect
28	Auto del FP	3	1.13 sec	0 %
27	Pitch only	3	1.21	29
9	Bank ind. B	4	1.24	33
8	Auto 6:1	6	1.31	5
24	Augie arrow	4	1.31	11
21	Bank ind. T	4	1.37	8
10	F-18 PL	3	1.39	0
20	Bank ind. T	4	1.39	25
19	Auto 2:1	3	1.41	29
--	Mean -----------		1.47 sec	--------
23	FP only	4	1.48	0
1	Baseline	5	1.48	12
18	Minute hand	5	1.54	11
11	Analog	3	1.55	8
4	Rt side PL	3	1.59	9
14	Auto A to D	3	1.61	18
6	6:1 scaling	4	1.63	43
7	2:1 scaling	7	1.64	16
3	+5/-2 PL	3	1.64 sec	36 %

Table XV

Objective Data Ranked by Percent Incorrect

	Display	No of flts	Reaction Time	Percent Incorrect
28	Auto del FP	3	1.13 sec	0 %
10	F-18 PL	3	1.39	0
23	FP only	4	1.48	0
8	Auto 6:1	6	1.31	5
21	Bank ind. T	4	1.37	8
11	Analog	3	1.55	8
4	Rt side PL	3	1.59	9
24	Augie arrow	4	1.31	11
18	Minute hand	5	1.54	11
1	Baseline	5	1.48	12
7	2:1 scaling	7	1.64	16
--	Mean			17 %
14	Auto A to D	3	1.61	18
20	Bank ind. T	4	1.39	25
27	Pitch only	3	1.21	29
19	Auto 2:1	3	1.41	29
9	Bank ind. B	4	1.24	33
3	+5/-2 PL	3	1.64	36
6	6:1 scaling	4	1.63 sec	43 %

Table XVI

Objective Data Ranked by Altitude Lost

	Display	No of flts	Altitude Lost
28	Auto del FP	3	111 ft
27	Pitch only	3	116
4	Rt side PL	3	312
11	Analog	3	317
19	Auto 2:1	3	342
3	+5/-2 PL	3	379
21	Bank ind. T	4	410
7	2:1 scaling	7	470
24	Augie arrow	4	515
23	FP only	4	516
10	F-18 PL	3	549
6	6:1 scaling	4	675
8	Auto 6:1	6	709
--	Mean	--------------	615 ft
9	Bank ind. B	4	892
20	Bank ind. T	4	947
1	Baseline	5	1168
18	Minute hand	5	1260
14	Auto A to D	3	1600 ft

Table XVIII

Pitch Scale Compression Objective Data Summary

	Display	No of flts	Reaction Time (sec)	Percent Incorrect (%)	Altitude Lost (ft)
8	Auto 6:1	6	1.31 (1)	5 (1)	709 (4)
19	Auto 2:1	3	1.41 (2)	29 (4)	342 (1)
1	Baseline	5	1.48 (3)	12 (2)	1168 (5)
6	6:1 scaling	4	1.63 (4)	43 (5)	675 (3)
7	2:1 scaling	7	1.64 (5)	16 (3)	470 (2)

Table XIX

Bank Index Objective Data Summary

Display	No of flts	Reaction Time (sec)	Percent Incorrect (%)	Altitude Lost (ft)
9 Grnd pntr(30)	4	1.24 (1)	33 (5)	892 (3)
24 Augie arrow	4	1.31 (2)	11 (2)	515 (2)
21 Enh sky pntr	4	1.37 (3)	8 (1)	410 (1)
20 Sky pntr(360)	4	1.39 (4)	25 (4)	947 (4)
1 Baseline	5	1.48 (5)	12 (3)	1168 (5)
26 Augie arrow plus grnd pntr		No objective data		

Table XX

Scales Format Objective Data Summary

Display	No of flts	Reaction Time (sec)	Percent Incorrect (%)	Altitude Lost (ft)
22 Imprvd MH	1	1.46 (1)	50 (6)	121 (1)
1 Digital	5	1.48 (2)	12 (4)	1168 (4)
18 Minute hand	5	1.54 (3)	11 (3)	1260 (5)
11 Analog	3	1.55 (4)	8 (2)	317 (3)
14 Anal to dig	3	1.61 (5)	18 (5)	1600 (6)
16 Auto delete	1	1.63 (6)	0 (1)	141 (2)

Table XXI

Longitudinal Format Objective Data Summary

	Display	No of flts	Reaction Time (sec)	Percent Incorrect (%)	Altitude Lost (ft)
28	Auto del FP	3	1.13 (1)	0 (1)	111 (1)
27	Pitch only	3	1.21 (2)	29 (6)	116 (2)
10	F-18 PL	3	1.39 (3)	0 (1)	549 (7)
23	FP only	4	1.48 (4)	0 (1)	516 (6)
1	Conv PL	5	1.48 (4)	12 (5)	1168 (8)
5	Both asymm	2	1.58 (6)	43 (8)	194 (3)
4	Lat asymm	3	1.59 (7)	9 (4)	312 (4)
3	Vert asymm	3	1.64 (8)	36 (7)	379 (5)

DISCUSSION

We shall examine the subjective and objective rankings for the various sets of formats flown during the simulations. These will include the effect of pitch scale compression, the bank index, the scales formats, and the other format issues. To do this, we will examine in turn the subjective and objective rankings. Objective rankings will be limited to reaction time and the percent incorrect (error percent).

Pitch Scale Compression

Table XXII lists the subjective and objective rankings for the various pitch scale compressions, one-to-one (baseline, symbology 1), two-to-one (symbology 7), six to-one (symbology 6), automatic two-to-one(symbology 19), and automatic six-to-one (symbology 8). The data was obtained from Tables IV and XVIII. The subjective rankings show a clear preference for two-to-one compression with six-to-one compression clearly not liked. Automatic compression switching was preferred in the two-to-one case, but not in the six-to-one case. Objectively, the reaction time data shows a preference for automatic switching and a preference for six-to-one over two-to-one compression. The error percent rankings show no clear effect.

The automatic six-to-one compression switching is an anomaly in these data. While the objective data indicates that it is superior, the pilots did not like the large compression changes. It is not clear why the full-time compressed pitch scales and the automatic compression changes should differ so in terms of objective data since seven of the eight UA entries exceeded the trigger and would have presented the compressed scaling. The eighth UA was at the trigger point (-30 degrees in pitch).

We suggest that the automatic two-to-one pitch compression is the favored format for UA recovery. The baseline (one-to-one scaling) and the full-time two-to-one compression formats are close behind. This conclusion is based to a large extent on the subjective evaluations which reject the six-to-one formats.

Bank Index Options

Examining the various bank indication options, we have no bank index (baseline, symbology 1), a ground pointer limited to 30 degrees (symbology 9), a sky pointer free to move through 360 degrees (symbology 20), a sky pointer enhanced when bank exceeds 58 degrees (symbology 21), the sky arrow on the velocity vector (symbology 24), and a ground pointer free to move through 360 degrees combined with the sky arrow on the velocity vector (symbology 26). The subjective data (from Table V) and the objective data (from Table XIX) are combined into Table XXIII.

The index on the velocity vector pointing up (Augie Arrow) shows a clear benefit. The subjective comments rated it well and the objective data showed a benefit in performance. This can be explained by the indication of bank in the center of the pilot's FOV. Since the pilots usually initiated UA recovery with a roll input, the result of having a bank index is obvious from the reaction times.

The choice of a sky pointer or a ground pointer is not clear however. The use of a sky pointer in the formats flown would tend to conflict with the heading index. In addition, the bank index chosen should agree with the pointer on the aircraft head-down attitude indicator. (Unfortunately, these are not at all standardized.) Further, the use of a ground pointer combined with the Augie Arrow could create interpretation problems.

The proposed choice would be a bank index at the top combined with an Augie Arrow. The heading scale should be relocated to the bottom of the display or to the horizon line as is down on most civil HUDs.

The bank index is most useful during instrument flight tasks since Air Force procedures emphasize precise bank angles(19). If the bank index were not needed or interfered with the balance of the HUD, it could be omitted.

Scales Formats

Examining the various airspeed and altitude scale options, we have digital scales (baseline, symbology 1), analog scales (symbology 11), digital scales surrounded by analog minute hands (symbology 18), an enhanced "minute hand" (symbology 22), scales that switch from analog to digital during unusual attitudes (symbology 14), and automatically deleting scales during UAs (symbology 16). Table XXIV summarizes the results for these cases (from Tables VI and XX). Symbologies 15 and 17 which combine scales change with pitch scale compression have been included in Table XXIV. However, the initial subjects flying these displays were so negative in their ratings and the first set of objective data was unfavorable that only limited data was obtained.

The data indicates that digital data is preferred and that the pilots felt that they can obtain enough rate information from the digital presentation. The minute hand indices were not rated well, however, the benefit of these may well be during routine instrument flight, not necessarily during UA recovery. The poor rating for the minute hand format is in disagreement with the Royal Air Force HUD symbology(20).

Other Format Options

Examining other options generally in the pitch ladder format and in the use of velocity vector, we have the comparisons in Table XXV. These data show a clear subjective preference for F-18 style pitch ladder and a clear objective improvement for recoveries using pitch information only. The subjective preference for automatic deletion of velocity vector was also high. These options are not mutually exclusive.

The various pitch ladder asymmetries were not well received by the subject pilots, nor was the objective data favorable. This does not agree with Taylor's results(4), although we have carried his approach to extreme in this study.

HUD Symbologies for Enhanced Unusual Attitude Recovery

Based on the results obtained, we can make some recommendations for HUD formats to minimize the pilot's likelihood of entering into an unusual attitude and maximizing his likelihood of recovering from the UA. It is to be remembered that these results are based on simulation, not flight. It must also be remembered that the various HUD symbologies were tried separately and not together. Before a final determination is made of the best symbologies, in-flight evaluations must be carried out.

Further, these formats are rated in terms of UA recognition and recovery. While an attempt is made to select those formats with minimal impact on operations, any final selection of a symbology must examine the effect of the HUD symbology on the mission of the airplane.

Pitch ladder cues

The benefit of complete lateral asymmetry was not shown by this study. It was anticipated that a pitch ladder on one side only would carry Taylor's approach(4) further. In fact, the lateral imbalance proved distracting to the pilots. The use of different pitch ladder spacing above and below the horizon likewise did not show any benefit.

The F-18 pitch ladder with slanted pitch lines pointing to the horizon was preferred by the subject pilots. It also showed a slight improvement in reaction time during UAs. We had intended to evaluate a pitch ladder with an F-18 slanted ladder below the horizon and a conventional ladder above the horizon, but a lack of simulation availability precluded this evaluation. It is an option that should be evaluated in any future studies.

The subjects also complained about the controlled precession as the aircraft pitch passed through the zenith or the nadir (90 degrees pitch up or down). This is an artificially induced action intended to emulate the action of early attitude indicators as they approached gimbal lock at the 90 degree up or down attitude. This makes controlled flight through these points quite difficult (and was reported as a means of inducing unusual attitudes for practice, Reference 13). We had planned to evaluate a non-precessing pitch ladder, however the pitch ladder orientation in the TASTEF simulator is provided by a machine language routine which could not be modified in the time frame available.

There is no need to maintain this controlled precession in any future electronic attitude indicators or HUDs. It was incorporated in an attempt to mimic a shortcoming of mechanical instruments and has no place in electronic displays.

Scales format

The conventional digital airspeed and altitude scales appear to be quite satisfactory. The concept of automatic declutter or a switch from analog to digital does not appear to be fruitful. (This applies to airspeed and altitude scales.) The lack of a digital heading indication was commented on by the subject pilots. The NT-33A HUD had a digital heading box superimposed on the analog heading scale.

The minute hand did not appear to help during UA recoveries. It is worth examining further for routine instrument flight, however.

At the same time, the pitch ladder should be redrawn to enhance heading awareness at extreme pitch attitudes. Freiburg and Holmström evaluated an ADI with enhanced heading information near the ninety degree pitch up or down point.(21) A similar approach would enhance HUD attitude awareness at extreme pitch attitudes.

Bank information

The presence of bank information had a very positive effect on both subjective and objective results. The arrow on the velocity vector was clearly preferred subjectively and second in both reaction time and percentage incorrect responses. The objective data for the combination of Augie Arrow and conventional bank index was lost because of a computer problem, however subjectively it was the clear choice.

It is not clear if a sky pointer or a ground pointer is preferred for a bank scale. It should be compatible with the pointer on the head-down ADI as installed on the aircraft. It should also be compatible with the Augie Arrow, if incorporated. This would suggest a sky pointer. The combined format test, however, was a ground pointer and the arrow on the velocity vector. Subjectively, this was not a problem.

The use of a sky pointer requires that the heading scale be modified to avoid interference. Since civil HUDs use the horizon as the heading scale, this should be followed as well with a sky pointer. A digital heading box above the waterline to show digital heading could be helpful. The Flight Dynamics HUD for the Boeing 727 uses a similar approach with some success.(22)

Pitch scale compression

The use of compressed pitch scaling was well received subjectively by the evaluation pilots. The use of two-to-one compression either automatically selected or full time appears to be a likely candidate for UA recovery enhancement. It appears that all non-ground referenced modes would be likely candidates for full-time two-to-one scaling. It is not clear if air-to-ground modes would benefit from such a choice.

It is clear that the use of compressed pitch scaling will require attention to the difference in angle between the waterline and the velocity vector. On most HUDs, the waterline is fixed in the FOV and the pitch ladder and velocity vector drawn relative to it. As implemented in the simulation, this created an incorrect angular relationship between the velocity vector and the waterline. If compressed pitch scaling is implemented in operational HUDs, it might be more desirable to draw the pitch ladder so that the horizon overlies the real world horizon or draw the pitch ladder such that the velocity vector symbol overlies the aircraft°s actual velocity vector. Any external target cues should overlie the actual location as viewed by the pilot.

One civil HUD uses a variable pitch compression for extreme nose-high or nose-low attitudes.(22) No problems were encountered during a simulator evaluation of this HUD.

Automatic deletion of velocity vector

One of the concerns during UAs is that the pilot will misuse the velocity vector and pull on the stick when already at a high angle-of-attack. One approach to this problem is to delete the velocity vector at large angles-of-attack. This format was rated highly by the subject pilots and had the best objective scores in every category. As implemented in operational HUDs, the velocity vector should be deleted when the angle-of-attack reaches a value where further pull should be discouraged.

If an Augie Arrow or angle-of-attack index is shown, they should be transferred to the waterline when the velocity vector is deleted.

Recommended symbologies

The following five composite symbologies are recommended for further consideration to enhance UA recovery and prevention and to determine effect on mission effectiveness. Composite symbology I is shown in Figure 5.

- Composite I:
  - o F-18 style pitch ladder below horizon and conventional pitch ladder above (pitch ladder modified to indicate heading when pitch exceeds +/-60 degrees -- no pitch precession passing zenith or nadir);
  - o Heading on horizon with digital heading above waterline;
  - o Bank index on top -- free to move through 360 deg (enhanced when bank exceeds +/-60 degrees);
  - o Change to two-to-one pitch scaling and display roll arrow on velocity vector symbol (or waterline) automatically when pitch exceeds thirty degrees or bank exceeds sixty degrees;
  - o Delete velocity vector automatically at high angle-of-attack (if Augie Arrow is being displayed, display on waterline symbol).

- Composite II:
  - o identical to Composite I except F-18 style pitch ladder with slanted pitch lines above and below horizon (pitch ladder modified to indicate heading when pitch exceeds +/-60 degrees -- no pitch precession passing zenith or nadir).

- Composite III:
  - o identical to Composite I except full time one-to-one pitch scaling.

- Composite IV:
  - o identical to Composite I except full time two-to-one pitch scale compression.

- Composite V:
  - o identical to composite I except full time Augie Arrow.

Table XXII

Pitch Scale Compression Rankings

For Unusual Attitude Recognition and Recovery

Pitch Scale Compression	Subjective			Objective	
	Ease of Flying	Ease to Maintain Orient'n	Over-all Rating	Reac-tion Time	Error Per-cent
19 Auto 2:1	2.2 (1)	2.2 (1)	2.2 (1)	1.41 (2)	29 (4)
7 Two-to-one	2.3 (2)	2.5 (2)	2.5 (2)	1.64 (5)	16 (3)
1 One-to one	2.6 (3)	2.9 (3)	2.9 (3)	1.48 (3)	12 (2)
6 Six-to-one	3.5 (4)	3.3 (4)	4.0 (4)	1.63 (4)	43 (5)
8 Auto 6:1	4.0 (5)	3.8 (5)	4.5 (5)	1.31 (1)	5 (1)

Table XXIII

Bank Index Rankings

For Unusual Attitude Recognition and Recovery

Bank Index Format	Subjective: Ease of Flying	Subjective: Ease to Maintain Orient'n	Subjective: Over-all Rating	Objective: Reac-tion Time	Objective: Error Per-cent
26 Augie arrow plus grnd pntr (360)	2.0 (1)	2.0 (1)	2.0 (1)	(a)	(a)
24 Augie arrow	2.3 (2)	2.3 (2)	3.0 (2)	1.31 (2)	11 (2)
1 No bank index	2.6 (4)	2.9 (4)	3.0 (2)	1.48 (5)	12 (3)
9 Grnd pntr (30)	2.3 (2)	2.7 (3)	3.3 (4)	1.24 (1)	33 (5)
21 Enhanced sky pntr	3.3 (5)	3.0 (5)	3.3 (4)	1.37 (3)	8 (1)
20 Sky pntr (360)	4.0 (6)	3.3 (6)	3.5 (6)	1.39 (4)	25 (4)

(a) Objective data not recorded due to computer error.

Table XXIV

Scales Rankings

For Unusual Attitude Recognition and Recovery

Scales Format	Subjective: Ease of Flying	Subjective: Ease to Maintain Orient'n	Subjective: Over-all Rating	Objective: Reac-tion Time	Objective: Error Per-cent
1 Digital	2.6 (1)	2.9 (1)	3.0 (1)	1.48 (2)	12 (4)
22 Enhanced MH	4.0 (4)	3.5 (3)	3.7 (2)	1.46 (1)	50 (7)
11 Analog	3.7 (3)	3.7 (5)	3.7 (2)	1.55 (4)	8 (2)
18 Minute hand (MH)	3.4 (2)	3.6 (4)	3.8 (4)	1.54 (3)	11 (3)
14 Analog to digital	4.3 (6)	3.7 (5)	4.0 (5)	1.61 (6)	18 (5)
16 Auto delete	7.0 (7)	7.0 (7)	7.0 (7)	1.63 (7)	0 (1)
15 Auto A>D/6:1 (a)	4.0 (5)	3.0 (2)	4.0 (5)	1.55 (4)	25 (6)
17 Auto delete/6:1	7.0 (8)	6.0 (7)	7.0 (7)	1.75 (8)	50 (7)

(a) One subject, ranking is probably not significant.

Table XXV

Longitudinal Format Rankings

For Unusual Attitude Recognition and Recovery

Scales Format	Subjective			Objective	
	Ease of Flying	Ease to Maintain Orient'n	Over-all Rating	Reac-tion Time	Error Per-cent
10 F-18 pitch ladder	2.7 (2)	2.0 (1)	2.3 (1)	1.39 (3)	0 (1)
28 Auto delete VV	2.7 (2)	3.0 (4)	2.7 (2)	1.13 (1)	0 (1)
27 No vel vector	3.0 (4)	3.0 (4)	3.0 (3)	1.21 (2)	29 (6)
1 Conv pitch ladder	2.6 (1)	2.9 (3)	3.0 (3)	1.48 (4)	12 (5)
23 No pitch symbol	3.3 (5)	2.8 (2)	3.3 (5)	1.48 (4)	0 (1)
5 Both asymmetries	4.5 (7)	3.5 (6)	4.0 (6)	1.58 (6)	43 (8)
4 Lat asymmetry	4.3 (6)	4.3 (7)	4.0 (6)	1.59 (7)	9 (4)
3 Vert asymmetry	5.0 (8)	5.0 (8)	5.0 (8)	1.64 (8)	36 (7)

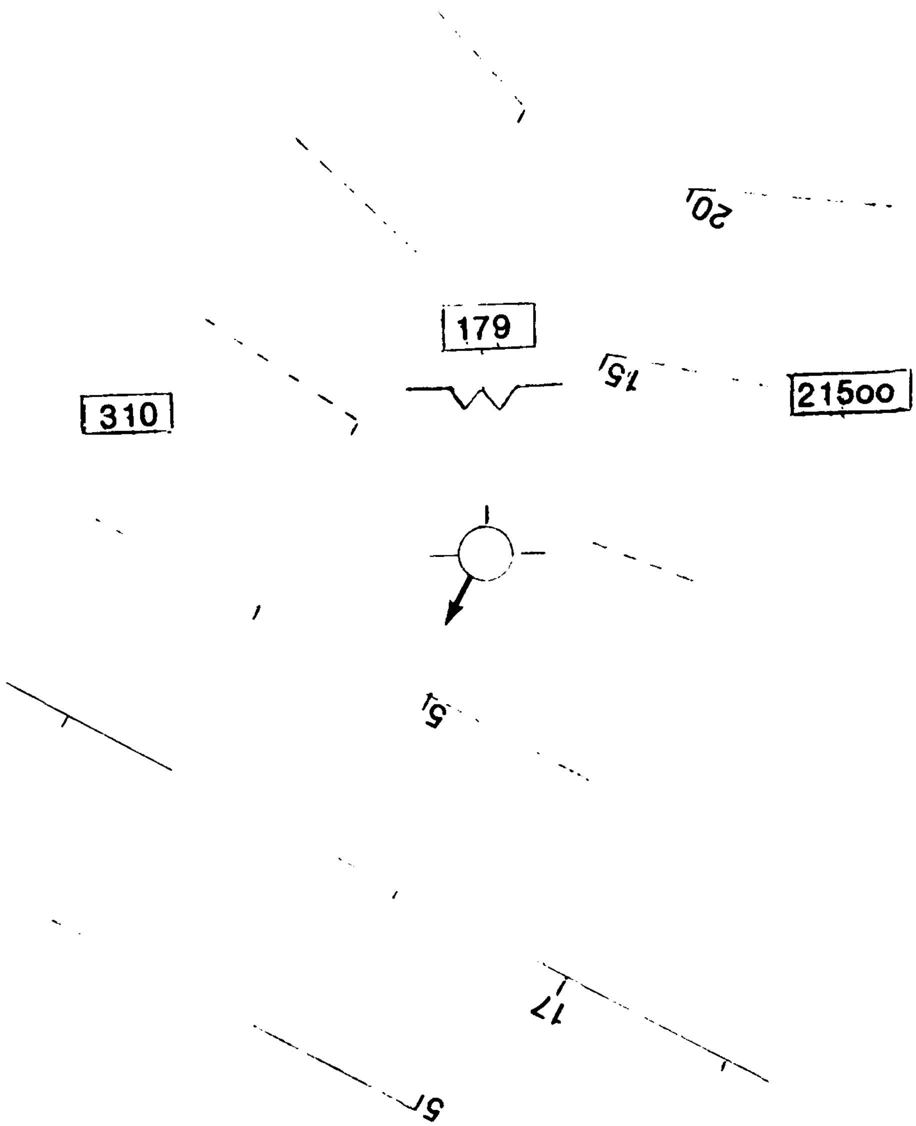

Figure 5

Composite Symbology I

CONCLUSIONS

The F-18 pitch ladder with slanted pitch lines pointing to the horizon enhances unusual attitude recovery. Since no adverse effects of such a pitch scale are likely, it can be recommended for inclusion in future HUDs. The modified F-18 pitch ladder with slanted pitch lines below and conventional pitch lines above the horizon may prove superior, but has not been tested.

Conventional digital airspeed and altitude scales appear to be satisfactory for unusual attitude recovery. Addition of analog rate cues did not enhance recovery.

The presence of bank scales has a very positive effect on unusual attitude recovery. A upward pointing cue on the velocity vector is an extremely effective cue aiding recovery.

The use of two-to-one pitch scale compression either automatically selected or present full time is quite helpful in unusual attitude recovery. The use of such compressed pitch scaling will require attention to the difference in angle between the waterline and the velocity vector.

Automatic deletion of the velocity vector at high angle-of-attack is very helpful during unusual attitude recovery. This method had the highest subjective and objective data rating during fixed base simulation trials.

Several candidate symbologies are recommended for further in-flight evaluation. An in-flight evaluation should be carried at in the near future to validate these findings. Such a flight program should include typical mission segments in addition to the unusual attitude recoveries.

RECOMMENDATIONS

Further evaluation of the four composite symbologies is recommended before implementing in an operational HUD. This evaluation should be undertaken with operational pilots in-flight. In addition to unusual attitude recoveries, the evaluation should include typical mission segments, including simulated air-to-ground attack, simulated air-to-air combat, low level cruise, and visual and instrument landing approaches.

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HEAD-UP DISPLAY GUIDE

Appendices

APPENDIX -- SUBJECT PILOT COMMENTS

Display 1 -- Baseline (also general comments from final questionnaire:

U: Wider/bolder horizon line.
Heading scale box.
Wider pitch lines.
Digits [on this HUD] are hard to read.

V: Don't enclose digital scales.
Airspeed and altitude digital scales need to incorporate larger and more distinct numbers. [Drew a sketch showing larger numbers for the thousands and hundreds of feet]. Nine hundred some feet can be easily mistaken for nine thousand some feet. Make thousands numbers bigger and use a preceding zero for altitudes below 1000 feet.
Bigger is better.
Colored horizon line.
If the waterline were a separate color with longer wings, instrument acrobatics might be easier.
F-16 vs. F-18 pitch ladder - under test conditions equally interpretable.
Broader heading scale.
Perhaps add a sky pointer.

W: Heading sometimes hard to read.

X: Put a sky pointer somewhere!
Confusion during over-the-top tumbling.

Y: Improve airspeed digits -- can't read.
Heading not parallel to horizon creates confusion during acrobatics.
Controlled precession over-the-top is terrible.

Z: Bank scale (preferably sky pointer - 360 deg).
More enhanced horizon line.
Waterline in some compressed modes did not correspond to actual pitch.

Display 2 -- 2 degree pitch ladder:

Z: Too many lines moving too fast.

Display 3 -- Different spacing above and below horizon:

U: Pitch ladder too busy in negative pitch.

V: Too many graduations in nose low pitch.

Y: 2 deg pitch spacing below horizon may be too close.
Probably OK for IMC.

Display 4 -- Pitch ladder on right side only:

X: Takes more time to decide if I was upright by studying whether pitch sca.e was on left/right.

Y: With lines on one side, the horizontal reference lines are too short for extreme attitudes when the horizon is not visible.
Seemed to be a tendency to get the "leans" and try to roll until HUD seemed symmetrical.

Z: Not enough reference. If pitch scale limited to one side, make lines longer.
Difficult to establish specific bank angles.

Display 5 -- Combine display 3 and display 4:

X: 2 deg gradations excessive, cluttered.

Y: Can't use vertical asymmetry; lines are too short. Need to be longer or on both sides.

Display 6 -- 6:1 scaling:

U: Easy to use, big picture.
Not as easy to fly precise attitudes.

V: 1/6 scaling does not provide the real time information for adequate return to level flight.

Y: Visual disparity with real world.
Slow motion leads to overcontrol.
Pitch symbol does not indicate actual pitch against scale.

Z: With visual cues, rate of pitch change did not correspond to pitch movement.
Waterline not tied to anything.
Not enough increments in [pitch] scale.
Became confused as to which way was up or down.
Can't make precise corrections.

Display 7 -- 2:1 scaling:

V: Seems a little better ratewise [than 6:1]. Try 3:1.

X: Display makes sense to me as a fighter pilot. No mirrors, chains, and pulleys.
Flight parameters change at a logical rate and crosscheck flows well.

Y: Visual disparity with real world.
Good for IMC at high altitude cruise.
Better than 6:1 scale for cruise.
Not sure about 6:1 versus 2:1 for acrobatics.
Like apparent slow rate during acrobatics.

Display 8 -- Auto 6:1 scaling:

U: The auto switching was very disorienting. Could lead to problems.

V: I though I would like this [see display 6], but found change was distracting.
Rate change was distracting and sometimes delays interpretation of attitude.

W: I do not like it!

Y: During acro, changes in apparent pitch and roll rates make it difficult to "finish" maneuver.
Heading rate not consistent with pitch and roll rate.
During unusual attitude recovery, the rates are very slow, easy to read pitch and roll.
1:1 changing to 6:1 might be too extreme.
Suggest override on stick to cancel.
Gain change at switchover disorienting.
Suggest hold 6:1 on recovery for a few seconds. Put in some hysteresis.
Suggest change spacing on pitch ladder so "real" angle between bars changes. i. e. for auto 6:1 don't make spacing 5 deg and 30 deg --look the same -- try 5 deg and 20 deg.

Z: Change in pitch scale rate is much more confusing than helpful.
During acro, you go from a dynamic to passive to dynamic presentation during various parts of the maneuver. I found this distracting.
During unusual attitudes, if attitude is right at changeover point when attitude is discovered, it is very disorienting initially.

Display 9 -- Bank scale (at bottom, limited to 30 deg):

V: Did not consciously use roll scale.

X: Remove bank pointer, I did not find it useful.

Y: Roll index very helpful for starting and finishing maneuvers.
Not very helpful at large bank angles.
Extend range of pointer.
Suggest change to "sky pointer."

Display 10 -- F-18 pitch ladder:

Y: Slanted pitch bars no problem. Definitely improve perception.

Display 11 -- Analog scales:

U: Analog scale is very usable.
Appears easy to read.
Scaling with larger airspeed and altitude at top is good.
Mechanization is very good.

V: I'd rather have digital information.

X: Rapidly changing airspeed/altitude scales are very distracting.
If you have no clue what your airspeed or altitude is, you must read, comprehend, and analyze figures which may be moving fast.
[Drew a picture showing digital scales.]

Display 14 -- Auto change from analog to digital:

V: Like change from analog to digital -- attention getting.
Good trend information.
Don't like analog scales for dynamic maneuvering.
Probably good for instruments.

W: Like the fact that it alerts you to a gross pitch or bank angle by changing the display.
However, once alerted, it takes some extra time to "mentally recompute" and refocus on the new display.
Suggest widening the change parameters.

X: This switching display will add one more request from the pilot. Build it one way and keep it that way until something better comes along.
If you must switch at 30 deg of pitch, don't have the switch at 60 deg of bank. That's really unnecessary and often distracting.

Display 15 -- Auto 6:1 and analog to digital:

V: Rate change and scale change is somewhat disconcerting. Don't changing scaling [analog to digital] -- try it with just rate [1:1 to 6:1].
6:1 scaling makes acro easier.

Display 16 -- Auto remove scales:

U: Not desired.

Y: Not flyable!

Display 17 -- Auto 6:1 and remove scales:

W: This version is dogsh--.

Y: Not flyable!

Display 18 -- Minute hand:

U: The minute hand is useful in giving trend information.

W: Don't really think big circles around scales do anything. Didn't use minute hand.

X: Don't use the spinning clock. I can read the numbers.

Y: Airspeed easier to control in intentional maneuvers. Trends easier to spot during unusual attitudes.

Display 19 -- Auto 2:1 scaling:

U: I feel it is very useful during unusual attitude recovery. Of all the different types of auto switching, I feel 2:1 is the least annoying to the pilot.

Y: Better than auto 6:1.
Compressed pitch should also compress difference between waterline and velocity vector.

Z: Didn't realize pitch scale was changing.

Display 20 -- Bank index (top, free to travel 360 deg):

U: Make bank pointer work in the direction of turn. Bank to right, pointer to right.

W: Would like pointer to point in the direction of turn -- not a sky pointer.

Z: The bank index helps, but because it is located away from the central vision reference, it must be looked for. Does not jump out at you and indicate a problem.
Bank symbology still gets lost in other symbology too much.
Reduce amount of heading segments to make bank symbology more commanding.
Bank index and scale at bottom of display.
Bank index and scale helps with making an accurate initial recovery input.

Display 21 -- Enhanced bank index (top, free to travel 360 deg):

U: Make bank pointer work in the direction of turn. Bank to right pointer to right.

W: Would like pointer to point in the direction of turn -- not a sky pointer.

Z: The bank index helps, but because it is located away from the central vision reference, it must be looked for. Does not jump out at you and indicate a problem.
Bank symbology still gets lost in other symbology too much.
Reduce amount of heading segments to make bank symbology more commanding.
Bank index and scale at bottom of display.
Bank index and scale helps with making an accurate initial recovery input.

Display 22 -- Enhanced minute hand:

U: Trend info is good. Plus relative position on needles is good 9 o'clock for 75 knots or 750 ft.
Good for overall big picture of approach speed and altitude.

W: The minute hands were useless. Didn't do a thing for me.

Y: Have to "look" around field-of-view for index.

Z: Put pointer on outside of circle or have line bisect circle.
Would be helpful for instrument approaches.

Display 23 -- No waterline:

U: Easier to level aircraft than with waterline only [display 27].
In a low airspeed situation with FPM/VV only, you may over control

Y: Have to "look" around field-of-view for index.

Display 24 -- Augie arrow:

U: Need a bank scale also.

Y: Very easy to maintain bank.
Very small transition for VV to bank.
Perhaps arrow on waterline.
Suggest increase size of arrow during unusual attitude

Z: Up is always obvious -- good general info and quick reaction possible.
Very good immediate reference and initial recovery response during unusual attitude recovery.
Because pointer is centrally located on display, there is no searching for a recovery reference.
Still like to see bank scale included.
For acrobatics: bigger wings on FPM and subsequently longer sky pointer.

Display 27 -- Delete velocity vector:

U: Waterline only would help the pilot relate the HUD to an ADI.
Must crosscheck to determine level flight.

Y: Difficult to level off after unusual attitude recovery.

Display 28/29 -- Auto delete velocity vector:

U: The idea has merit to delete the VV/FPM as you approach a high AOA.
I feel that even though the VV/FPM has disappeared, the pilot will use the waterline instead.
Modify to occur only at very high angle of attack.
No problems during unusual attitude recovery.

Y: Good -- shows alpha limit clearly.

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